PERMEANCE OF CONCRETE TO AIR
AND WATER VAPOR

by

MUFID A. SAMARAI

B. S., Robert College, Istanbul, Turkey, 1959

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1961

TABLE OF CONTENTS

INTRODUCTION	1
LITERATURE REVIEW	6
WATER MOVEMENT THROUGH CONCRETE	14
SELECTION OF METHOD	16
MATERIALS	19
APPARATUS	20
PROCEDURE	22
DISCUSSION OF RESULTS	29
CONCLUSION	39
ACKNOWLEDGMENT	42
LITERATURE CITED	43
APPENDIX	45

INTRODUCTION

Engineers have long recognized permeability as one of the most important qualities of concrete. However, this quality in concrete has received comparatively little attention in the many laboratory studies which have been carried on to establish the properties of concrete. Because of the limited available sources of published information, it was difficult to acquire an intimate knowledge of the subject in its various phases. Yet, many of the concrete failures could be attributed to the permeability and absorptive qualities of the concrete. Structures valued at many millions of dollars are now showing deterioration where they are exposed to water and freezing weather. In many instances, the deterioration has progressed to a point where it is jeopardizing the structures, and millions of dollars will have to be spent on repairs and replacements within the next decade to keep them in serviceable condition.

The extensive use of concrete in structures for hydraulic power developments, harbor works, irrigation, water supply, and other construction fields has brought to the attention of engineers that water-tightness may be of even greater importance than compressive strength (9). The importance of impermeability is not just a matter of confining the water to its proper channels, for almost any concrete carefully made and cured will prevent serious loss of water through percolation. The real need for water-tightness is to prevent the disintegration which

results from the freezing of saturated, porous concrete or slow deterioration through the solution of essential ingredients. It takes only a brief survey of structures which have been exposed to severe climatic conditions to appreciate how important is the destructive effect of frost where the concrete is readily permeable. Structural failures of concrete are extremely rare, and can usually be traced to a disregard of well established principles of making, placing and curing concrete. The penetration of moisture followed by freezing or even by alternate wetting and drying has caused marked deterioration of concretes which have apparently been produced with proper materials and methods, and which also have had the requisite structural strength. To insure long life under such conditions of exposure, concrete of low permeability must be produced. Many investigators seem to agree that high compressive strength will result in low permeability for any given materials provided consistencies or flowabilities are limited to the minimum suited to the type of work. This relation between impermeability and high compressive strength seems to be as accurate as any of the so-called laws of proportioning concrete for compressive strength.

As was mentioned before, concrete permeability implies fluid passage as capillary or by water vapor movement. Only the latter of these types of movement is of importance for our present study. The behavior of moisture is too often overlooked or given scant attention in the design and construction

of buildings. It is present as a vapor in all air, and as adsorbed moisture in most building materials. It may also be present, at times, in the free liquid state or as ice in the solid state, within the range of temperature encountered in many buildings. Problems involving moisture may arise from changes in moisture content, from the presence of excessive moisture, or from effects associated with its changes in state.

Moisture problems in residences occur in winter and become increasingly important as homes are built smaller and tighter. Water vapor originates from such necessary living requirements as cooking, laundering, bathing, and the breathing and perspiration of people. In a typical family of four, the average daily production of water vapor from these sources may be as much as 25 pounds, and may be much greater where such appliances as humidifiers, automatic washers, and dryers are used. A large source of water vapor is sometimes the bare earth in a crawl space or basement.

One of the most significant effects of water-vapor permeance could be the corrosion of steel bars in reinforced concrete construction. Reinforcing steel, when embedded in concrete, should be relatively passive to corrosion. In an alkaline solution a protective film of gamma ferric oxide ($Fe_2 O_3$), which is impervious to ions, forms on the steel and prohibits additional corrosion. However, due to insufficient cover of concrete, cracking and/or excessive permeability, the atmosphere

can readily penetrate to the reinforcement; then normal atmospheric corrosion may occur.

A vivid example of the damage that corroded reinforcement can do is the failure of a number of precast I-beams supporting the roof of lumber-drying kilns at the Brunswick-Balke-Collendar Company's plant at Muskegon, Michigan. The beams were exposed to the warm, moist atmosphere inside the kilns, and the only protection for the reinforcement was that provided by the concrete of the beams themselves; which is usually thin in this type of beam. The kilns were built in 1947, and corrosion proceeded at such a rate that, in some of the beams, bars of seven-eights of an inch in diameter were reduced to one-half inch or less by the summer of 1955. Failure occurred only under the dead load of the roof. Although the concrete was of fair quality (small specimens cut from the beams tested between 3,000 and 4,000 psi), the steel had so little covering that both moisture and air penetrated readily. The steel corroded, and because the oxide occupied a larger volume than the steel, the bars increased in size and literally burst the beams. The longitudinal steel caused very noticeable cracks, which often extended the full length of the beam along one or more faces of the flanges. The three-eights of an inch diagonal web bars, in several cases, simply popped the concrete from one face of the web, leaving the steel exposed.

An entirely different corrosion problem exists when sodium chloride, which may be introduced into the concrete as salt

contamination of the aggregate, by the use of sea water, or by the permeation of salt spray, is present in the concrete. This type of corrosion may cause a decrease in reduction of area of the steel, but of much greater consequence for reinforced concrete is the fact that the products of corrosion set up high, expansive forces, cracking and spalling the concrete over the reinforcement. This condition has been observed to be one of serious magnitude in the Pacific Area, and in many other marine localities. Air conditioning of reinforced concrete structures, which accelerates the permeation of moisture and accompanying salt toward the cold interior, may intensify this problem.

The investigations described in this thesis were limited to the passage of water vapor through concrete made with three kinds of aggregates for two thicknesses of specimen; to only one concrete mixture; to three curing periods, and to one temperature and vapor difference.

The principal objects of this study were

1. To develop a simple, inexpensive method for determining the permeance of concrete to vapor and air,

2. to investigate the influence of different types of aggregates, curing, thickness of concrete cover, head of concrete and coatings on permeance of concrete,

3. to prove this method by comparing the effect of variables with those which have been adequately studied previously on water, and

4. as a pilot investigation to develop techniques and apparatus that would be useful in extending the investigation.

LITERATURE REVIEW

Much literature is available discussing the permeability of concrete and it all agrees that concrete is permeable. The fluid usually is water and may exist as liquid or as water vapor, or as a mixture of water vapor and air. For any condition under which water passes through a given material, a general equation may be written between the forces acting and the resulting flow. Such an equation takes into account the fact that the amount of flow of fluids through any permeable medium is a function of three variables: (1) the inherent property of the material to resist flow, (2) the area subject to permeability, and (3) the force tending to produce flow. This relationship is represented by a general equation known as Darcy's law: $Q = K'A\frac{H}{L}$

(a) Stated for the flow of liquids (saturated flow) Darcy's law may be applied to concrete as was done by Ruettgers, Vidal and Wing (16),

where Q = discharge quantity, unit volume in unit time,

H = head of fluid,

L = percolation length,

A = gross area subject to percolation,

and

K' = permeability coefficient for concrete under consideration.

(b) For capillary movement of moisture this same relationship may be stated as was done by Richards (4) for soils

$$Q = K'' A \nabla \Phi$$

where $\nabla\Phi$ is the total water-moving field or the total field tending to produce motion of the water; for example, the pressure force and gravity.

(c) Applied to vapor permeability situations, the formula may be used as was done by Barre (1) in the form

$$Q = K''A \frac{dP}{dL}$$

where dP is the vapor pressure differential causing vapor movement.

Powers and Brownyard (14) found, from studies of fresh paste made of water and normal portland cement, that for water-cement ratios up to about 0.5 by weight, the flocculated cement particles formed a continuous structure. At such water ratios, the mass of paste constitutes one continuous floc, and the permeability of the mass as a whole depends on the floc texture. At very high dilution the particles form flocs that are more or less independent of each other. The permeability of such a mass is not determined by the floc texture, but largely by the size of the undivided flocs and their concentration. On the other hand (17) the homogenity of fresh paste, or the lack of it, probably persists in some degree after the paste

hardens. Hence, it is probable that for hardened pastes having water-cement ratios greater than 0.6, the permeability of a test disk is determined not only by the permeability of the hardened paste, but also by the vertical channels that represent discontinuities in the paste--the discontinuities that developed during the bleeding period.

It is apparent that an increase in the number of fissures per unit area of paste would increase the permeability of the paste, since such fissures present less resistance to the passage of water than does the texture of the paste itself.

With respect to the relationship between the permeability of a paste (as discussed above) and the permeability of concrete Powers (14) states,

> Introduction of aggregate particles into paste tends to reduce the permeability by reducing the number of channels per unit gross cross-section and by lengthening the path of flow per unit linear distance in the general direction of flow. However, during the plastic period, the paste settles more than the aggregate and thus fissures under the aggregate particles develop. In saturated concrete these fissures are paths of low resistance to hydraulic flow and thus increase the permeability of the concrete. In general, with a paste of a given composition and with graded aggregate the permeability is greater the larger the maximum size of the aggregate. Obviously, the permeability of the concretes as a whole is much higher than the theoretical permeability developed for a homogeneous medium.

Most of the published literature on the permeability of concrete describes the results of investigations on the passage of water through concrete under pressure. The pressure used varied from 40 lbs. per sq. in. to 500 lbs. per sq. in. The

permeability characteristics of a concrete appear to vary as the pressure acting to force the water through the pore structure varies. Hence it is difficult to correlate the results of the several investigations except in very general terms.

In 1928, Collier (3) published a paper describing a method for determining the flow of water through concrete; the water being under a pressure of 145 lbs. per sq. in. This was one of the earliest papers written on the subject. Although his apparatus was rather complicated and not too accurate, his tests have shown: (1) a general, straight-line, relationship between flow of water through concrete and water-cement ratio when the data are plotted to logarithmic scale; (2) that the flow decreased as the cement content was increased, although no definite relationship was established; and (3) that the flow decreased with a decrease in fineness modulus.

Similar investigations by Norton and Pletta (11) carried out on gravel concrete showed that the relationship of permeability to water-cement ratio is influenced considerably by the consistancy and, especially with the leaner mixes, by the grading of the aggregate. More water is required for minimum permeability than for maximum strength, the permeability increasing when the water is reduced below the amount required for a slump of about two to three inches.

An extensive study of the subject was carried out by McMillan and Lyse (9) when they studied different variables

with principal attention given to the factors which govern the quality of the paste. The possible differences in placing methods were brought out.

It was found that the specimens, jigged 10 times on a standard flow table, with one-half inch drops, showed greater water-tightness during the first two days, but thereafter the leakage was the same as for the specimens molded by rodding in the usual way. The importance of curing was also brought out in this investigation. Specimens placed under test at three days showed several times as great a permeance as similar specimens cured for seven days before placing them under test.

The great effect of curing made it necessary to test the specimens in that investigation at early ages because, with the mixes ordinarily used in concrete practice, it was found that specimens were so nearly watertight, if cured for the more usual period of twenty-eight days, that no important results could be obtained from the tests. When tested at the early age, the effect of continued moist-curing, in increasing the water-tightness, tended to reduce the leakage with duration of the tests more rapidly than would be the case if the specimens had been tested at the advanced period.

Ruettgers (15), in discussing the above paper, suggests as an explanation for the diminution in flow from specimens with duration of test, the constriction of the pores through further swelling of the specimens from increased water saturation. In

addition to this, the continued hydration and obstruction of the passages with silt or other impurities in the water could be other possible causes.

Moreel (10), in reviewing the laboratory work carried at Ponts et Chaussees, states:

> Concretes aged under water are much less permeable than concretes which have been allowed to age in air; the latter, however, became less permeable when subjected to water under pressure and tended to approach the condition of concrete aged under water.

He also added,

> Concretes aged in air, the permeability decreases with age; for concretes aged in water there was no appreciable improvement in water-tightness after the concrete was eight days old.

The majority of the investigations upon which reports are available have been confined to concretes made up of relatively small, maximum-size aggregate. The work of Ruettgers, Vidal, and Wing (16) was initiated in connection with preliminary investigations of the concrete for Hoover Dam. Consequently, the investigation was extended to include the larger sizes of aggregate that would be used in the mass concrete, (up to and including the 9-inch maximum size). The data reported show a consistent increase in permeability accompanying the increase in maximum size of aggregate. This may be explained, at least in part, by the settlement of the progressively smaller particles away from the larger particles of the mass during the plastic condition. This settlement produces voids of relatively low hydraulic resistance under the aggregate particles,

and under pressure would permit water to pass quite readily.

Many investigators (9, 18) have attempted to improve the water-tightness of concrete by addition of certain admixtures. In general the results of their tests confirm the fact that the performance of too many of the so-called waterproofing materials do not come up to the claims made for them. The influence of such additives would be less than those that would be secured from the use of adequate amounts of cement and proper curing methods. It must be noted here, that the addition of any inert material as a void filler cannot completely fill the voids. It must necessarily occupy space and have enough of the impervious cement paste to completely coat it in order to be beneficial in promoting impermeability.

Numerous determinations of the water-vapor permeability of such materials as paint films and wrapping and packaging materials have been made by different investigators. Investigations have also been made on building plasters, papers, and boards, including moisture-proofing treatments; but, to date, only a few investigations have been reported on concrete.

Barre (1), in 1937, made some tests on the water-vapor permeability of concrete. He used two test methods. In one method, small concrete tanks constructed from special precast units were filled with water and subjected to conditions of ordinary room temperatures and humidities. The inside surfaces of some of the tanks were treated with different kinds of paints.

The water in the tanks, especially in those without treatment, disappeared with surprising rapidity, although no liquid moisture was apparent on the outside surface. A considerable amount was also lost in some of the tanks with waterproofing treatments.

In the other method, concrete specimens $1\frac{1}{2}$ in. in thickness were subjected to a difference in vapor pressures on the two faces of the specimen. The amount of moisture permeating the specimens was condensed on a cold surface and collected. The results showed that even high-strength concretes are permeable to water vapor, although it is known that they are permeable to (3) liquid-moisture even under high liquid pressures. In concluding his paper Barre stated,

> Moisture losses from untreated surfaces of concrete tanks which emerge in the form of vapor raised the question as to the method by which moisture passed through concrete. The latter tests clearly indicated that the concrete was permeable to water vapor even when no liquid was in contact with the surface. Other correlated tests clearly showed that this same concrete would permit the passage in the amount by the action commonly referred to as capillarity. This series of tests seem to have the value in establishing, at least tentatively, the magnitude of vapor and capillary resistance of the type tested under conditions of these tests.

Griffin and Henry (7) studied the permeance of concrete to water-vapor at the same time the present studies were carried out. They used the wet-cup method in their tests. The dry-cup method was used in this study for reasons that will be brought up later. In different parts of this paper reference

will be made to the work of the two authors and, hence, no further discussion of their work will be mentioned now.

WATER MOVEMENT THROUGH CONCRETE

The Building Research Advisory Board Report No. 14, to the Federal Housing Administration (7), has summarized the current professional thought concerning the method by which water moves through concrete as follows:

> The Committee (Advisory Committee of BRAB) believes that moisture is transferred through partially dry concrete in the absorbed or condensed state by surface diffusion and does not move as vapor through concrete. Also, where good practice has been followed in the design and curing of concrete, it is believed that moisture does not move through the concrete by capillarity as it is usually understood. The transfer process is considered to be the same where either liquid water or water vapor are present directly beneath a slab-on-ground. However, other conditions being similar, there is believed to be a much slower transfer to the absorbed state when vapor rather than liquid water is in contact with the slab. This results in a slower rate of moisture transfer through the slab where only vapor is present.

Further,

> Due to the hygroscopic nature of concrete it is believed incorrect to consider the rate of moisture transfer proportional to the vapor pressure differential between a moist and a dry side of a slab. This is because moisture moves through a mature concrete in an absorbed or condensed state and not in a vapor phase. For water moving through concrete in a condensed state, the driving force is not computed from the difference between the two pressures but from the ratio between the two relative humidities.

Results of this study support to a certain extent some of the above statements. Specimen I-3 which was cured for twenty-eight days and was started in cup I-1 with the same silica gel as that of I-1, gained almost the same amount as that of I-2 which had a fresh silica gel but identical properties. This proves that even though the absorptive power of I-3 was greater than that of I-2, because the ratio between the two relative humidities was constant, the permeability was not altered greatly.

On the other hand, several objections have been made to this hypothesis. There is some doubt about diffusion in solid solution being fast enough to account for the relatively high permeability to moisture of such materials as concrete. Another important objection advanced is that solid solution of water is incompatible with X-ray evidence, in that water does not enter the crystallites, shown by the fact that the dimensions of the crystal lattice remain unchanged when the water is taken into the structure.

One thing is definite though, the movement of moisture through porous or granular solids is a complicated phenomenon that cannot be solved completely by any single approach. A great deal of investigation is needed in the future to solve and understand this complex phenomenon.

SELECTION OF METHOD

Permeability is definitely a more complex physical property than compressive strength. Certainly the apparatus for permeability determination as used by most investigators was so complex that it became very hard to duplicate or to conduct extensive studies with it. In planning permeability test apparatus, specimens and procedure, it is believed that careful consideration should be given to practical application of the test data secured. Otherwise it may be found less difficult to secure the data than to convert the results to a form for ready comparison or to apply them to the solution of concrete design problems.

None of the permeability apparatus used for water permeability measurements were applicable to water-vapor permeability. The only alternative left in selecting the apparatus for the present study was to try to use the methods used in fields, other than concrete, for the determination of water-vapor permeability.

There were many methods used for the determination of permeability of membranes to water-vapor, especially packaging materials. The most common of these were four methods which could be described briefly as follows:

Method A. The specimen is fastened over the mouth of a dish or cell (usually a crystallizing dish) containing water, or an aqueous solution of high relative vapor pressure. Loss of moisture through the specimen to a drier atmosphere is determined from successive weighings. This method is called the wet cup.

Method B. As in method A, the specimen is fastened over the mouth of a dish or cell, which, however, contains a desiccant. The gain in weight of the cell serves to measure the amount of moisture passing through the specimen and into the cell from a moist atmosphere on the outside. This method is called the dry cup.

Method C. The specimen is a septum between a moist stream of air and a dry stream of air. Moisture that passes through the septum appears as an excess weight in one moisture train or as a deficiency in the other.

Method D. The specimen is a septum separating saturated water vapor from an evacuated space consisting essentially of a flow tube with an ionization gage at each end. The vacuum pump is kept going and the water-vapor flow meter measures at any time the rate of flow of moisture through the specimen.

The first two methods were the most used and were the best for our purpose. They are also recommended by the American Society for Testing Materials as standard methods for measuring permeance of building materials, other than concrete,

for water vapor. The latter two methods were discarded. The wet cup was used in the studies carried on by the Navy Department at the same time these studies were under way. The difference between these methods; namely, the wet-cup and dry-cup, was considered to be very little, but the dry-cup method was selected because it was easier to use, and there were more facilities in the laboratory for its usage.

The main reason for selecting the dry-cup was the fact that a reduction in thickness of the air space under the concrete could be more conveniently made in this method than in the wet-cup method. The importance of this phenomenon was best explained by Carson (2) who stated,

> The diffusion of water vapor through still air is relatively slow, an influence that has in large measure been ignored. In most tests of water-vapor permeability that have been made, at least one face of the membrane has been in contact with a layer of still air separating it from the humidifying or the desiccating agent. If the rate of flow of moisture through the membrane is great enough to prevent a substantially uniform distribution of moisture within the air space, the usual assumption that the vapor-pressure difference across the membrane is given by the known over-all vapor-pressure difference is subject to considerable uncertainty.

He then continues,

> Although the effect of diffusion through intervening air spaces may be small when relatively impermeable materials are tested, it seems logical, especially in the case of the more permeable materials, where the effect may be large, to minimize this effect by reducing as much as possible the thickness of the layer of air confined in the test cell, and to provide sufficient circulation on the exposed face of the membrane to prevent an appreciable

> vapor-pressure gradient from existing outside the membrane. Otherwise it is very difficult to know much about the vapor pressure difference across the membrane itself. The reduction in the thickness of the air space under the membrane is more conveniently made in the dry cup method than in the wet cup method, which seems to be an important point in favor of the use of a solid desiccant in the cell rather than water or other liquid agent.

Another fact in favor of the dry-cup method was that it is always easier and more accurate to handle and weigh a solid desiccant than a liquid. After all of these factors were taken into consideration the dry cup method was selected for this study.

MATERIALS

The cement used was a standard brand Type I portland cement, purchased on the open market under the brand name "Lone Star Cement". Three sacks of cement were stored in a large galvanized iron bin which was made as airtight as possible. The cement had the following physical and chemical properties:

Physical Properties	Chemical Analysis
Loose weight, 94 lb./cu. ft.	Calcium oxide, 63.23%
Normal consistency, 23%	Silicon dioxide, 20.77%
Specific surface, 3380 sq. cm/gm. Blaine	Aluminum oxide, 5.90%
Autoclave, 0.102 soundness	Ferric oxide, 2.82%
Initial set, 4 hrs. 50 min.	Magnesium oxide, 2.77%
Final set, 6 hrs. 00 min.	Sulphur trioxide, 2.30%
Tensile strength	Ignition loss, 1.07%
3 days, 370 lb./sq. in.	Total, 98.86
7 days, 470 lb./sq. in.	
Fineness, 85.5	
Specific gravity, 3.15	

Commercial sand was used having the following physical properties:

Specific gravity, 2.63
Unit weight (dry rodded) 111.40 lb./cu. ft.
Absorption, 0.5%
F. M., 3.71

Three types of aggregates were used having the following properties:

	Limestone	Gravel	Quartzite
Specific gravity	2.50	2.58	2.62
Unit weight	101.80	106.46	105.32
Absorption (%)	5.5	2.36	0.60
Fineness Mod.	5.47	6.34	5.5
Maximum size	½ in.	½ in.	½ in.

The water used in mixing the concrete was from the college supply obtained from wells.

The sand was air dried, before it was used, by spreading it on the floor of the testing laboratory in front of an electric fan, and raking it occasionally. The aggregates were air dried also.

The cement and aggregates for each batch were weighed on a scale sensitive to 0.05 lb., and the water on a scale sensitive to 0.01 lb.

APPARATUS

A simple and common method of making water vapor permeability was used in this study. The apparatus consisted of a cup on top of which the specimen was sealed. A desiccant was

placed inside the cup and the apparatus was then placed in a constant temperature humidity room. The amount of moisture passing through the specimen was determined by the gain of weight of the cup and its content. This gain was recorded at equal intervals as water vapor permeability of the specimen.

Silica gel was used as the desiccant because it has a powerful affinity for water and a high drying efficiency; that is, a low vapor pressure after absorbing a large amount of water. The silica gel was in the form of small lumps that passed a No. 8 sieve, and free from finer that passed the No. 30 sieve.

Several types of cups were tried resulting in the final adoption of the cylindrical plastic cups. The cups were cut from 3-inch diameter plastic bottles. The plastic cups were found to be very practical and easy to handle as well as being light in weight. There was no possibility of the cups corroding due to the silica gel or of not being tight enough to allow the moisture to escape.

The specimens were cut from 3 by 6-inch molds that were cured for the required time in the humidity room and then cut by a bricksaw to the required thickness. Several materials were then considered for use in sealing the concrete disks in the cup; a sealer that would bond both to the concrete and the plastic cup, would be inert, and would be impervious to water vapor. An electricians plastic tape was found to meet these requirements.

Although there was a tight seal between the specimen and the cup, a few of the specimens were stopped due to leakage between the cup and specimen. This leakage was caused by the chipping off of the concrete specimens while being cut. Later, the method was modified by using a coating on the sides of the specimens to fill the chipped portion of the concrete. This was found to be effective. The coating used was an epoxy resin.

The moistroom, a fog room, had a constant humidity of 100 per cent, and constant temperature around 71° F. The pressure difference on both sides of the specimens, hence, was about 0.37 lb. per sq. in.

The apparatus is shown in Plate I.

PROCEDURE

After the apparatus was selected the next step was to decide on a concrete mix. The mix was selected to be not too impermeable nor too permeable but rather moderate as far as permeability was concerned. The same general mix was used for all three types of aggregates. The mix selected with a typical calculation of the materials is given in the Appendix. Mixing was performed in a Lancaster mixer and both the mixing operation and the molding of the specimens were carried out in accordance with the designated procedures of the American Society for Testing Materials.

EXPLANATION OF PLATE I

A. Assembled cup with 150 grams of silica inside the cup, and one-inch thick specimen.

B. Assembled cup with 150 grams of silica inside the cup, and two-inch thick specimen.

C. One-inch thick specimen before being assembled on top of the cup.

PLATE I

In most cases 3 by 6-in. molds were used, except for specimens where the head effect was to be studied, then 3 by 12-in. molds were used. All of the specimens were cured in 100 per cent RH for the desired period of time.

All specimens were cut by a bricksaw from locations specifically designated on the cylinder as T (top), M (middle), B (bottom), as cast. The specimens were 1 in. thick unless otherwise specified. The following random numbers were given to the cylinders for dry-cup specimens,

Limestone designated	I-1 to I-6
Quartzite designated	II-1 to II-5
Gravel designated	III-1 to III-5

Where 3 by 12-in. molds were used the letter "A" was written after the number; i.e., IIAT or IIAB. In cases where 2-in. thickness was used the letter X was written after the number; i.e., IIXT or IIXB, etc.

Then the apparatus was assembled as previously described and the dry-cup assembly was weighed and put into the controlled humidity room. Once a week for three weeks the cup was taken out from the room, surface dried, and weighed again. Cups I-1T, I-2T and I-6T were weighed every day the first week, and the results are reported in Fig. 1. The results obtained from these tests are given in Table 1.

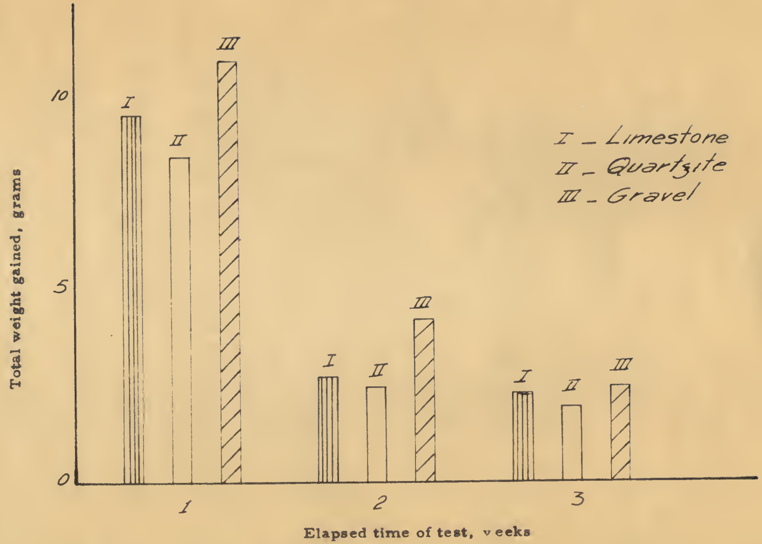

Fig. 1. Weight gained by 7-day cured concrete vs elapsed time of test.

Table 1. Total weight gained in grams.

Cup No.	Time of Rdg. (Weeks)	Slice T	Slice M	Slice B
I-1 [1]	1	9.62	4.94	2.90
I-1	2	12.50	7.44	4.20
I-1	3	15.06	9.39	5.69
I-2 [2]	1	8.6	5.17	2.54
I-2	2	10.5	8.33	4.10
I-2	3	15.10	10.81	5.00
I-3 [3]	1	8.70	6.40	2.95
I-3	2	10.28	8.71	3.84
I-3	3	15.00	10.70	5.44
I-4 [4]	1	7.10	---	2.08
I-4	2	8.59	---	3.58
I-4	3	11.39	---	4.44
I-5 [5]	1	0.21	---	0.10
I-5	2	0.57	---	0.81
I-5	3	0.93	---	1.01
I-6 [6]	1	3.37	3.20	1.14
I-6	2	5.53	---	1.89
I-6	3	7.29	---	2.48
II-1 [7]	1	8.6	3.2	2.71
II-1	2	11.11	3.8	4.00
II-1	3	13.21	12.3	5.25
II-2 [8]	1	4.14	---	2.05
II-2	2	7.07	---	2.85
II-2	3	8.20	---	3.90

[1] 7 day curing, 1" thick limestone, 3" x 6" molds.
[2] 28 day curing, 1" thick limestone, 3" x 6" molds.
[3] 28 day curing, 1" thick limestone, 3" x 6" molds, started in cup I-1.
[4] 50 day curing, 1" thick limestone, 3" x 6" molds.
[5] 50 day curing, 1" thick limestone, 3" x 6" molds, top and sides coated with sika.
[6] 28 week curing, 1" thick limestone, 3" x 6" molds.
[7] 7 day curing, 1" thick quartzite, 3" x 6" molds.
[8] 28 day curing, 1" thick quartzite, 3" x 6" molds.

Table 1. (concl.)

Cup No.	Time of Rdg. (Weeks)	Slice T	Slice M	Slice B
IIX3 [1]	1	2.78	---	1.10
IIX3	2	3.58	---	1.85
IIX3	3	4.15	---	2.04
II-4 [2]	1	2.82	1.50	1.04
II-4	2	4.64	5.10	1.94
II-4	3	5.25	6.30	2.30
IIA1 [3]	1	9.24	32.41	1.92
IIA1	2	12.02	38.64	2.80
IIA1	3	15.10	46.74	3.60
IIA2 [4]	1	5.40	---	1.51
IIA2	2	8.63	---	1.86
IIA2	3	9.34	---	2.46
IIA3 [5]	1	2.85	1.8	0.82
IIA3	2	4.80	3.0	1.20
IIA3	3	5.87	3.7	1.66
III-1 [6]	1	11.01	4.56	4.20
III-1	2	15.15	8.38	6.98
III-1	3	17.65	14.96	8.16
III-2 [7]	1	11.27	7.09	2.38
III-2	2	20.5	---	4.03
III-2	3	23.9	---	5.92
III-3 [8]	1	3.96	---	1.32
III-3	2	6.30	---	2.12
III-3	3	8.34	---	2.72

[1] 28 day curing, 2" thick quartzite, 3" x 6" molds.
[2] 28 week curing, 1" thick quartzite, 3" x 6" molds.
[3] 7 day curing, 1" thick quartzite, 3" x 12" molds.
[4] 28 day curing, 1" thick quartzite, 3" x 12" molds.
[5] 28 week curing, 1" thick quartzite, 3" x 12" molds.
[6] 7 day curing, 1" thick gravel, 3" x 6" molds.
[7] 28 day curing, 1" thick gravel, 3" x 6" molds.
[8] 28 week curing, 1" thick gravel, 3" x 6" molds.

DISCUSSION OF RESULTS

Due to the fact that the data taken from this study was very limited, and not very consistent, it does not seem right to draw extensive conclusions. However, the data show that the apparatus, with some improvement, could provide very accurate and reliable results.

It could be easily seen that permeability decreased with the duration of the test. The permeability the first few days was much larger than the permeability after two or three weeks. Many specimens sealed themselves almost entirely within the first two weeks. To a certain extent, this was to have been expected from the continued hydration during the early period of moist curing which was found to be of extreme importance. The time the specimens were under test was actually a moist-curing period, and at least part of the decrease in permeability found by increased length of test can be accounted for in this manner. As a possible further cause for the diminution in flow from specimens with the duration of the test, the possible obstruction of the passages with impurities and the constriction of the pores through further swelling of specimens from increased water saturation might tend to reduce the flow.

A clear illustration of the effect of duration of test on the flow through the specimen is given in Fig. 1. The

specimens in this figure represent the top slice of three different aggregates cured for seven days. The figure shows that the amount of weight gained the first week was greater than twice that for the second week. Specimen I gained about 9.62 grams of water the first week and only 2.88 grams the second, and as low as 2.56 the third week. Specimens II and III behaved in the same pattern. However, specimens I and II which had lower permeability the first week than specimen III, which showed a more uniform decrease throughout the duration of the test.

In order to study the phenomenon of duration of test further, Fig. 2 is presented. In this figure the two specimens shown are I-1 and I-6. Specimen I-1 was cured for 7 days while specimen I-6, which had the same properties as I-1 except for period of curing, was cured for 28 days. The uniformity of the curves showed that the specimens gained weight very steadily and uniformly; the specimens cured for longer periods being more uniform.

Aside from the interesting comparison just made with respect to the curves in Fig. 2, the data are of interest also with reference to the effect of curing on permeability. In fact, the really significant conclusion to be drawn from these data is that two weeks additional curing reduces the moisture tightness of concrete to one half. The importance of this will be further brought out in the discussion of curing.

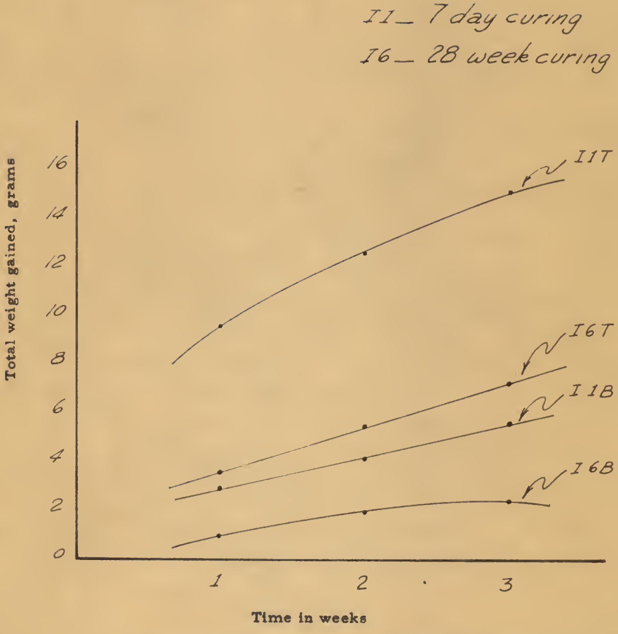

Fig. 2. Weight gained by Type I concrete vs time.

The tremendous importance of proper consolidation and the head depth of concrete is obvious from the results obtained. The effect of head of concrete was tremendous on all the specimens except for specimen I-5 which was coated with an epoxy resin. All of the specimens showed an appreciable difference in the gain of moisture between the top and bottom slice of the same mold, the top being higher. This seems to be reasonable since the bottom slice would be denser due to the head of concrete.

Table 1 gives a striking proof of the effect of the head of concrete. The difference between the top and bottom slice seems to be great, with specimens IIA1 to IIA3 showing the greatest difference. These three specimens were specially made to study the effect of concrete head on permeability. The permeability of IIA1 to IIA3 as compared to II-1 to II-3 is shown in Fig. 3. Both of these specimens, namely, IIA and II, were made with quartzite which showed the lowest permeability among the three aggregates studied. Specimen II-1 to II-3 were standard specimens cut from 3 by 6-in. molds, while specimens IIA1 to IIA3 were made from 3 by 12-in. molds. Examining Fig. 3 we can see that the top slices of specimen IIA gained greater amounts of moisture than their equivalent from specimens II. On the other hand, the bottom slices in all of the 3 by 12-in. specimens gained less moisture than the bottom slices of the 3 by 6-in. specimen. This is nothing

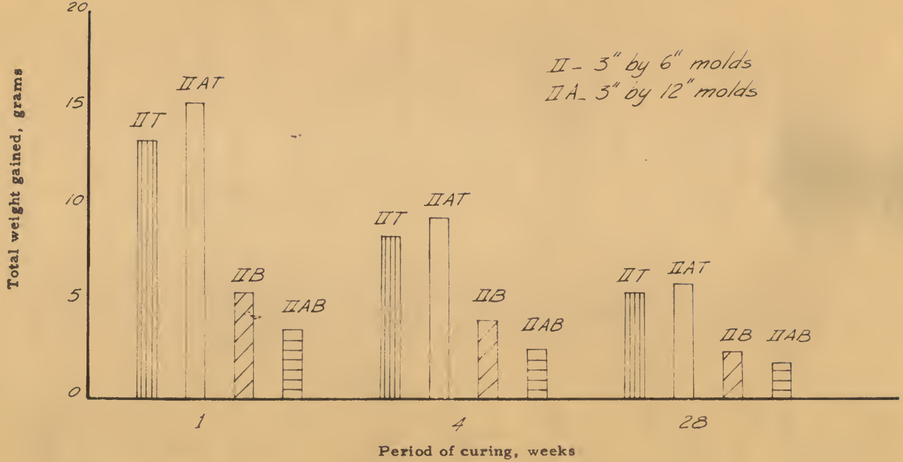

Fig. 3. Effect of concrete head on the permeability.

but a further proof of the importance of the proper consolidation and placing of the concrete.

The greatest difference between the top slice and the bottom one was in specimen IIA1. Specimen IIA1 was cured for seven days and cut from 3 by 12-in. molds. The difference was as high as 61.5 per cent. Specimen II-1 which had the same properties as IIA1, except it was cut from 3 by 6-in. molds, showed a difference of 43.3 per cent. Specimen IIA2, cured for four weeks, showed a difference of only 58.2 per cent, and specimen IIA3, cured for 28 weeks, showed a lesser difference of 54 per cent. This shows that better curing could reduce the effect a little but not to such an extent as to warrant neglect of care in placing the concrete.

To study the effect of the epoxy resin under the commercial name of "Sika", on the permeability of concrete for vapor, two specimens I-4 and I-5 were prepared. Both of these specimens were cured for 50 days and were made with limestone as an aggregate, and from 3 by 6-in molds. Specimen I-5 was coated on the sides and the top with Sika, while specimen I-4 was coated on the sides only. The effect of the coating was tremendous and astonishing. The top slice of I-5 gained only 0.93 grams and the bottom 1.01 grams during the three weeks of test. The top slice of I-4, without the coating, gained about 11.39 grams of weight while the bottom gained about 4.44 grams. From this comparison it could be concluded that exterior coating could be very effective. More extensive study is needed to

give a more definite and satisfactory conclusion.

The effect of thickness on permeability has been proven by many investigators (9, 14) to vary directly as the square of the thickness with the permeability of concrete to water. To study the effect of thickness on the water vapor and air permeability of concrete, two specimens II-3 and II-4 were made. Both of these specimens had quartzite as an aggregate and were cured for a period of 28 days. The only variable between them was the thickness of the slice tested, specimen II-3 being one inch thick while specimen II-4 was two inches thick. The results of this study are shown in Fig. 4.

Figure 4 definitely affirms the common and logical belief, which scarcely needs any proof, that permeance varies inversely with thickness. The top slice of II-3 gained about 8.20 grams of weight whereas specimen II-4, with 2-in. thickness, gained 3.90 grams of vapor as compared to 2.04 grams gained by the 2-in. thick slice. Although the proven fact that permeability varies inversely with thickness could be readily observed from Fig. 4, still no definite rule or pattern of variation could be stated without further studies.

The type of aggregate used in concrete has some effect on the permeance of concrete, although all of the aggregates used in concrete practice could be considered impermeable to a fair degree. The three aggregates used were limestone, gravel, and quartzite, each having specific gravities of 2.5, 2.58, and 2.65 respectively.

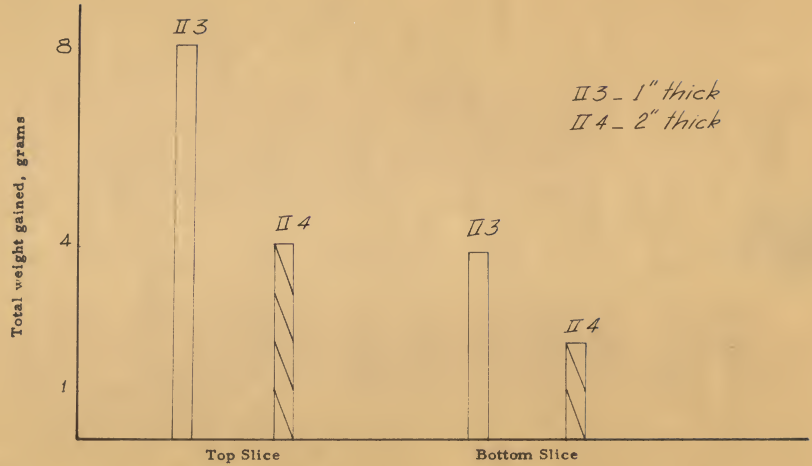

Fig. 4. Effect of thickness of specimen on the permeability.

Figure 1 was drawn to study the effect of the aggregates on the permeability of concrete containing them. The specimens shown were cured for seven days and were made from 3 by 6-in. molds. The only variable between them was the aggregate, designated in specimen I as limestone, in specimen II quartzite, and in specimen III gravel. Fig. 1 shows that gravel showed the highest gain of moisture in the three weeks of test. As was expected, quartzite had the lowest gain. The difference of gain of the three specimens was reduced during the third week; no explanation for this could be offered.

The important effect of the length of moist curing and age of specimens on the permeability has already been brought up in discussing the effect of test duration on permeability. For example, in Fig. 2 the leakage through a specimen, which was placed under test at seven days, was more than twice as great as that through a similar specimen that had been allowed to cure 28 weeks before being tested. Also, in Fig. 3, four specimens placed under test for three weeks, a very decided improvement in impermeability was shown for the specimen cured for 28 days moist as compared with those cured only seven days moist, and a far greater advantage for those cured 28 weeks.

In Fig. 5 the data used in plotting Fig. 2, and other data, are replotted to bring out more prominently the effect of length of moist curing. In this figure the permeability of the three concretes, with three different aggregates, are shown

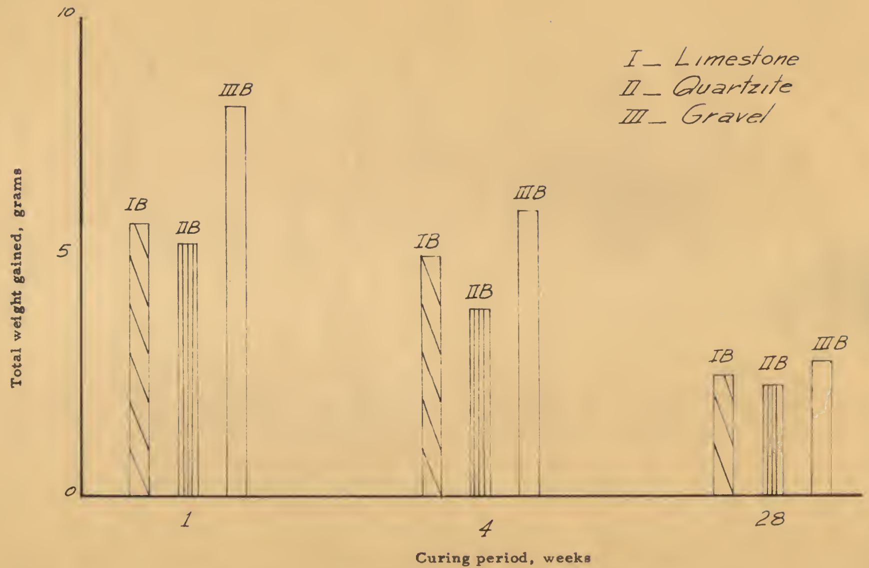

Fig. 5. Effect of curing period on total weight gained by the three types of concrete aggregates used.

for the three periods of curing. All the specimens in this group being the bottom slice of the mold and having the same thickness, the difference in weight gain indicated is due entirely to the effect of the additional hydration resulting from the extra time in the moist room for each type of concrete. Aside from the difference shown by the same type of concrete, the three types did show the same general trend of reduction in permeability with respect to elapsed curing period.

As pointed out in an earlier section, it was believed necessary to use a rather common mix in this investigation, because with richer mixes sometimes used in concrete practice the specimens would be so impermeable if cured for long periods of time that no important results could be obtained from the tests in the time available. When tested at the early ages, the effect of continued moist curing in increasing the impermeability tends to reduce the permeability with duration of the tests more rapidly than would be the case if the specimens had been tested at a later period. This could be seen, without any explanation, from results in Fig. 3 and Fig. 5.

CONCLUSION

This investigation has developed a method of making water-vapor permeability test that is quickly and easily made and operates satisfactorily, though some modifications may be

desirable if the investigation is to be continued. The data obtained have been consistent to a certain extent, and if the test is modified, very reliable data could be obtained. In the light of this investigation, it can be said:

1. The permeability test is a very sensitive test due to the many variables in the composition of concrete itself as well as in its texture.

2. The tests have demonstrated what has been observed in concrete structures that defects in placing may be a much more important factor in the permeability than ordinary differences in materials of curing period.

3. The most significant results of the tests are those showing the effect of continued moist curing in increasing the impermeability of concrete. Tests using these longer moist curing periods showed very rapid increase in impermeability with increase in length of moist curing period. These increases held, regardless of the other factors in the tests, showing that the length of moist curing is a primary factor in the building up of impermeable concrete.

4. Suggestions for changes in techniques of specimen preparation and testing are enumerated as follows:

   a. The cylinders could be placed in a prismatic mold and quick-setting plaster of Paris could be cast around it. This could be done to avoid chipping of the disks at the break-through of the saw.

b. The test might be carried out in a room with humidity less than the 100 per cent humidity used in this test. This should be effective in reducing the condensation of water on the face of the disks while being tested. It would, however, be more difficult to control the humidity at the desired constant level. Condensation of water might also be reduced if the cups would be laid on their sides rather than kept vertical.

c. It has been observed by the Navy Department that in making permeance tests using the wet cup method, drops of water tend to gather on the bottom of the concrete disk under test. In any atmosphere at or near 100 per cent relative humidity it is virtually impossible to avoid condensation, the dew point.

ACKNOWLEDGMENT

The writer wishes to express his gratitude to his research advisor, Professor C. H. Scholer, Department of Applied Mechanics, Kansas State University, whose valuable aid as a guide and in making suggestions, as well as continued encouragement during this study, made this paper materialize.

LITERATURE CITED

(1) Barre, H. J.
Some Observations of the Water Vapor Permeability of Concrete. A.S.T.M. Proc. 39:860-865, 1939.

(2) Carson, F. T.
Permeability of Membranes to Water Vapor with Special References to Packaging Materials. Misc. Pub. M127, Nat. Bureau Standards, 1937.

(3) Collier, I. L.
Permeability of Concrete. A.S.T.M. Proc. 28:490-496, 1928.

(4) Dunagan, W. M.
Methods for Measuring the Passage of Water Through Concrete. A.S.T.M. Proc. 39:866-880, 1939.

(5) Foster, B. E.
Use of Admixtures as Integral Water-proofing Materials. A.C.I. Proc. 47:46-52, 1951.

(6) Friedland, R.
Influence of Quality of Mortar and Concrete upon Corrosion of Reinforcement. A.C.I. Proc. 47:125-139, 1951.

(7) Griffin, D. F., and R. L. Henry.
Water Vapor Transmission of Plain Concrete. A.S.T.M. Research Session of A.C.I., 1960 Regional Meeting, November 2, Tucson, Arizona.

(8) McDermott, P. F.
Moisture Migration. Refrigeration Engineering, August 1941.

(9) McMillan, F. R., and Inges Lyse.
Some Permeability Studies of Concrete. A.C.I. Proc. 26:101-142, 1929.

(10) Moreell, B.
Permeability of Concrete. A.C.I. Proc. 31:571-572, 1934.

(11) Norton, P. T., and Dan Pletta.
The Permeability of Gravel Concrete. A.C.I. Proc. 27:1093-1132, 1931.

LITERATURE CITED (concl.)

(12) Pearson, J. C.
Low Head Permeability Test of Mortar Pots. A.C.I. Journal 35:285-297, 1939.

(13) Powers, T. C., L. E. Copeland, J. C. Hayes, and H. M. Mann.
Permeability of Portland Cement Paste. A.C.I. Proc. 51:285-298, 1954.

(14) Powers, T. C., and T. L. Brownyard.
Studies of the Physical Properties of Hardened Portland Cement Paste. Part 7, Permeability and Absorptivity. A.C.I. Proc. 43:865-880, 1947.

(15) Ruettgers, A.
Discussion of Ref. (9) A.C.I. Proc. 26:645-647, 1929.

(16) Ruettgers, A., E. H. Vidal, and S. P. Wing.
An Investigation of the Permeability of Mass Concrete, with Particular Reference to Boulder Dam. A.C.I. Journal 31:382-416, 1935.

(17) Shermer, C. L.
Corroded Reinforcement Destroys Concrete. Civil Engineering 26:56-57, December 1956.

(18) Wiley, George, and D. C. Coulson.
A Simple Test for Water Permeability of Concrete. A.C.I. Journal 9:65-75, 1937.

APPENDIX

CONCRETE MIX COMPUTATIONS

Limestone Sp.G = 2.50

Sand Sp.G = 2.63

Use 50% Stone

Use 50% Sand

Cement $5\frac{1}{2}$ sacks/cu. yd.

Water 6 gallons/sack of cement

1 Sack Batch	Absolute Vol.	Weight
Cement $\frac{5.5 \times 94}{3.15 \times 62.4}$	2.70 cu. ft.	530 lbs.
Water $\frac{6 \times 5.5 \times 62.4}{7.48}$	5.21 cu. ft.	326 lbs.
Sand $\frac{27-7.91 \times 2.63 \times 62.4}{2}$	9.55 cu. ft.	1535 lbs.
Stone $9.55 \times 2.50 \times 62.4$	9.55 cu. ft.	1495 lbs.
	27.01 cu. ft.	3886 lbs.

1 cu. ft. Batch

Cement $\frac{530}{27} = 19.65$ lbs.

Water $\frac{326}{27} = 12.10$ lbs.

Sand $\frac{1535}{27} = 57.00$ lbs.

Stone $\frac{1495}{27} = 55.10$ lbs.

Total ... 143.85 lbs.

PERMEANCE OF CONCRETE TO AIR AND WATER VAPOR

by

MUFID A. SAMARAI

B. S., Robert College, Istanbul, Turkey, 1959

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1961

Much literature is available discussing the permeability of concrete and it all agrees that concrete is permeable. The fluid usually is water and may exist as liquid or as water vapor, or as a mixture of water vapor and air. Much research work has been carried out on the permeability of concrete to water, but almost no work has been done on the permeability of concrete to water vapor and air.

One of the most significant effects of water vapor permeability is the corrosion of steel bars in reinforced concrete construction. If the steel has little covering, then both moisture and air would penetrate readily, and cause the steel to corrode. Because the oxide occupies a larger volume than the steel, the bars increase in size, and burst the cover over the steel. An entirely different corrosion problem exists when sodium chloride, which may be introduced into the concrete as salt contamination of the aggregate, by the use of sea water, or by the permeation of salt spray, is present in the concrete. This type of corrosion may cause a decrease in reduction of area of the steel, but of much greater consequence for reinforced concrete is the fact that the products of corrosion set up high, expensive forces, cracking and spalling the concrete over the reinforcement. This condition has been observed to be one of serious magnitude in the Pacific Area, and in many marine localities. Air conditioning of reinforced concrete sturctures, which accelerates the permeation of moisture and accompanying salts toward the cold interior, may intensify this problem.

The principal objects of this study were

1. To develop a simple, inexpensive method for determining the permeance of concrete to water and air,

2. to investigate the influence of different types of aggregates, curing, thickness of concrete cover, head of concrete and coating on permeance of concrete,

3. to prove this method by comparing the effect of variables with those which have been adequately studied previously on water, and

4. as a pilot investigation to develop techniques and apparatus that would be useful in extending the investigation.

A simple method of measuring water vapor permeability was used in this study. The apparatus consisted of a cup on top of which the specimen was sealed. A desiccant was placed inside the cup, and the apparatus was then placed in a constant temperature humidity room. The amount of moisture passing through the specimen was determined by the gain of weight of the cup and its content. This gain was recorded at equal intervals as water vapor permeability of the specimen.

In the light of this investigation, it can be said

1. The permeability test is a very sensitive test due to the many variables in the composition of concrete itself, as well as in its texture,

2. the tests have demonstrated what has been observed in concrete structures that defects in placing may be a much more important factor in the permeability than ordinary differences in materials or curing period, and

3. the most significant results of the tests are these showing the effect of continued moist curing in increasing the impermeability of concrete.